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Fault Current Limiting Characteristic of Non-inductively Wound HTS Magnets in Sub-cooled LN_2 Cooling System

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Abstract-- **An advanced superconducting fault current limiter (SFCL) using high-T_C superconducting (HTS) wire has been developed. The SFCL has a non-inductively wound magnet for reducing loss in normal state. Two types of non-inductively wound magnets, the solenoid type and the pancake type, were designed and manufactured by using Bi-2223 wire in this research. Short-circuit tests of the magnets were performed in sub-cooled LN_2 cooling system of 65 K. The magnets are thermally more stable and have a higher critical current in 65 K sub-cooled LN_2 cooling system than in 77 K saturated one. Because the resistivity of matrix at 65 K is lower than the resistivity at 77 K, the magnets generate a small resistance to reduce the fault current when the quench occurs. The magnets could limit the fault current to low current level with such a small resistance. The current limiting characteristic of the magnets was analyzed from the test result. The solenoid type was wound in parallel to make it non-inductive. The pancake type was also connected in parallel to be compared with the solenoid type in the same condition. The solenoid type was found to have a good thermal stability compared with the pancake type. It also had as large resistance as the pancake type to limit the fault current in sub-cooled LN_2 cooling system.**

1. INTRODUCTION

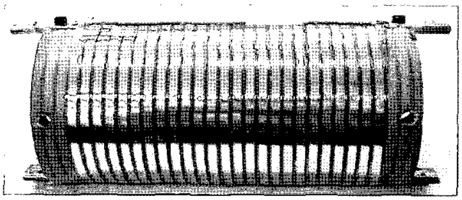
Damage from a fault current in present power transmission and distribution network is a constant threat to the electric power application these days. Since existing circuit breakers no longer cope with enlarging fault current, the SFCL has been developed in many research groups. The SFCL has effects on increase of interrupting capacity and breaking internal force in power system [1][2]. The non-inductively wound HTS magnet has been employed as one of the current limiting devices for the SFCL. The resistive type SFCL using HTS wire should be wound non-inductively to reduce the loss by making very small impedance before the fault occurrences.

In this research, two types of non-inductively wound HTS magnet were designed and manufactured. Because sudden thermal increase can be generated by the unexpected fault current in cryogenic system of the SFCL, the thermal stability of cryogenic system is very important in the SFCL. The profitable cooling method for the SFCL is sub-cooled nitrogen cooling method [3][4]. We performed short-circuit tests of non-inductively wound HTS magnets in sub-cooled nitrogen, 65 K, to increase the magnet stability and to increase critical current of the magnets [5]. Fault current limiting characteristics of non-inductive wound magnets were analyzed from the experimental results by comparing with two types.

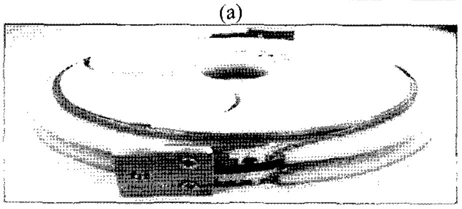
2. DESIGN AND MANUFACTURE OF HTS MAGNETS

2.1. The Solenoid Type Magnet

Each magnet was wound with stainless steel reinforced Bi-2223 wire of American Superconductor Corporation (AMSC). This HTS tape has about 125 A of critical current at 77 K, under self field. The width and thickness are 4.1 mm and 0.3 mm, respectively. Fig. 1(a) shows the solenoid type non-inductively wound HTS magnet. The magnet was wound with two HTS wire, inner and outer winding connected in parallel. The bakelite bobbin whose inner diameter and outer diameter are 78 mm and 100 mm respectively has grooves for non-inductive winding. There are four copper blocks for winding terminal at the end of the grooves. The inner and the outer winding were wound in counter direction and the kapton tape was wound between the inner winding and the outer winding for



(a)



(b)

Fig. 1. Non-inductively wound magnets. (a) solenoid type (b) pancake type.

insulation. Total length of HTS wire in the magnet was 15 m. The normal resistance of the magnet at room temperature was 139 mΩ and the inductance is about 0.5 μH.

2.2. The Pancake Type Magnet

The winding machine for the HTS pancake was used for bifilar winding. This machine gave the magnet constant winding tension by powder breaker. The pancake type bobbin was made of glass fiber reinforced plastic. To make non-inductive winding, the bobbin whose outer diameter is 210 mm has unique curved path on it and two adjacent wound wires should have current flow in counter direction. A HTS wire was wound along the curved path on the bobbin. It is the most efficient for non-inductivity winding of the other bifilar windings because it can totally cancel off magnetic field. Total length of HTS wire in the module was 7.5 m. In order to make the same condition as the solenoid type magnet, two pancake type magnets were connected in parallel. These pancake type magnets in parallel is shown in Fig. 1(b). The inductance and the resistance at room temperature were 0.3 μH and 141 mΩ, respectively. The pancake type magnets were impregnated by epoxy resin to protect the HTS wire against the physical force such as vibrating and magnetic force. The parameters of magnets and HTS wire are summarized in Table I.

3. EXPERIMENTAL SETUP

3.1. Sub-cooled nitrogen cooling method

The magnets were cooled down with sub-cooled nitrogen. The operating temperature of cooling system was 65 K and the pressure was maintained about 1atm. The cooling system using the 65 K sub-cooled nitrogen increased the critical current and thermal stability level of the HTS magnets. To make the sub-cooled nitrogen, a single-stage cryocooler whose capacity is 120 W at 80 K was installed to a cooling system. The cooling copper plate was connected to the coldhead of cryocooler and cooled down. The saturated liquid nitrogen of 77 K was cooled to the sub-cooled nitrogen of 65 K by this system. We could reduce the cooling time by using vacuum pump.

TABLE I
PARAMETERS OF HTS WIRE AND MAGNETS

HTS wire		
Material	BSCCO 2223 with Ag alloy sheath	
Width	4.1 mm	
Thickness	0.3 mm	
Critical current	125 A (77 K, self-field)	
Non-inductively wound HTS magnets		
Type	Solenoid	Pancake
Inner diameter of winding	98 mm	210 mm
Outer diameter or winding	98.6 mm	220 mm
Height of bobbin	200 mm	35 mm
Length of HTS wire	15 m	15 m
Inductance	0.5 μH	0.3 μH
Resistance @ 300 K	139 mΩ	141 mΩ

3.2. Experimental Setup for short-circuit test

The SFCL has ability to reduce the fault current by introducing resistance when the HTS wire is quenched due to over current above critical current. The short circuit tests are required to know the quench characteristics of non-inductively wound HTS magnets. The test was performed at single phase power system. Fig. 2 is the schematic of the short circuit test circuit. Because of the limitation of electric power source, the maximum available current by power source was set to 75 Arms. In order to enlarge the current flowing through the magnet, a 22:4 ratio transformer was introduced. The actual source of the test circuit is the secondary winding voltage of transformer. The current in secondary winding flows through the load whose impedance is 0.3 or 0.5 ohm before the fault occurrences. The fault duration was set to be 0.1s, 6 cycles in 60Hz power system.

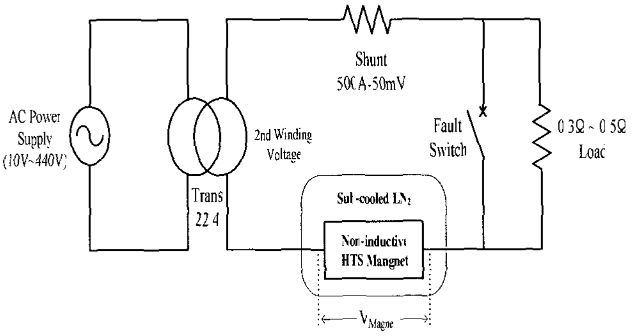


Fig. 2. Schematic of the short circuit test.

4. EXPERIMENTS AND DISCUSSIONS

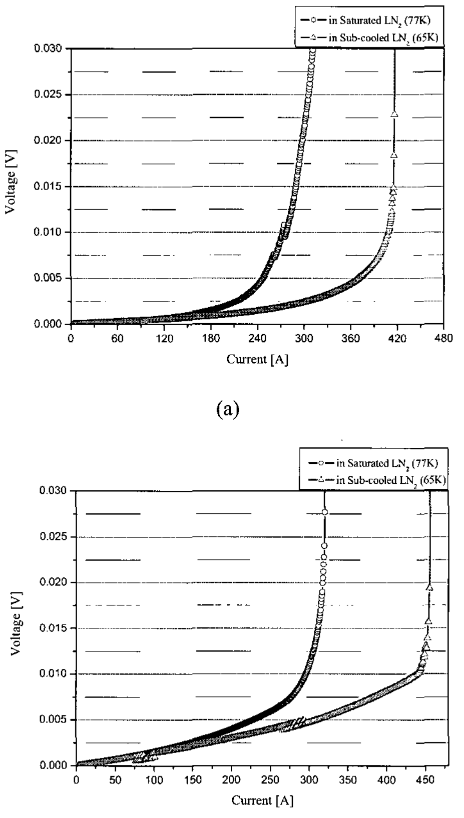
4.1. I-V Characteristic of Magnets

I-V curves of the magnet were measured at 77 K and 65 K by using universal power supply. The current ramping rate was 1 A/s. The voltage taps were attached on copper terminals. The voltage signal was caused by copper terminals as well as superconductor. Therefore, to decide the critical current using just these curves by 1μV/cm criterion is not appropriate. Fig. 3 shows I-V characteristics of the magnet at 77 K and 65 K. The current at the point of 10μV/cm in these curves was the modified critical current of the magnet. The critical currents of the solenoid type non-inductive magnet were 280 A at 77 K and 410 A at 65 K as shown in Fig. 3(a). The critical currents of the pancake type magnet at 77 K and 65 K were 300 A and 440 A respectively as, shown in Fig. 3(b). Because non-inductively wound HTS magnets had a structure canceling the magnetic field around wire, the measured critical current was higher than the expected critical current by critical current in parallel structure.

4.2. Results of the short-circuit test

To operate the FCL in 65 K sub-cooled nitrogen has several advantages. The critical current of the magnet was increased as shown in Fig. 3. The HTS magnet is more thermally stable in sub-cooled nitrogen.

There also exist a few advantages in the FCL application. The resistance of the HTS magnet for the SFCL descends as the temperature becomes lower. Resistances of the solenoid type magnet as the applied voltage of 29.1 Vrms at 77 K and 65 K were compared in Fig. 4.



(a)

(b)

Fig. 3. Critical current at 77 K and 65 K. (a) solenoid type (b) pancake type.

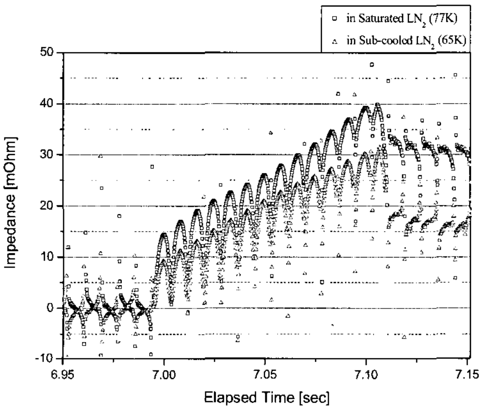
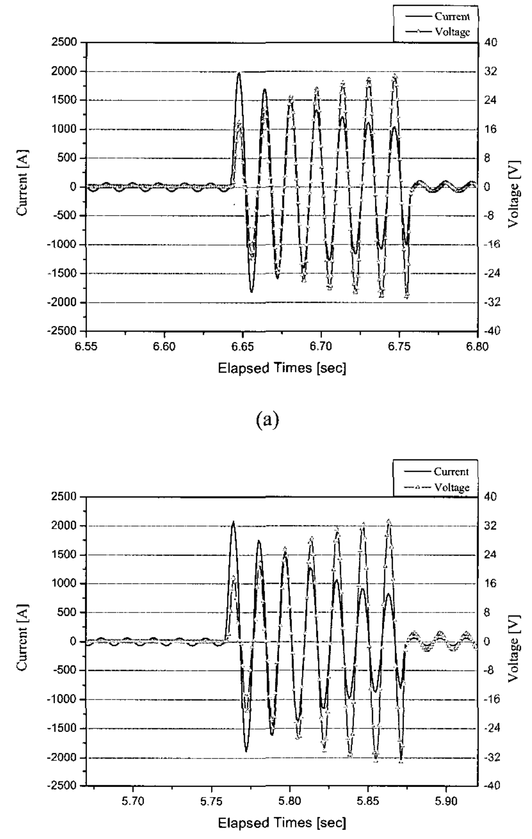


Fig. 4. Resistances of the solenoid type at 77 K and 65 K.

Fig. 5(a) and (b) are experimental results of solenoid and pancake type magnets respectively at applied voltage of 29.1 V_{rms} in 65 K Sub-cooled LN_2. The fault current without SFCL can be estimated about 4250 A_{peak} from calculated line impedance [6].



(a)

(b)

Fig. 5. Test results at 29.1 V_{rms} test (a) solenoid type (b) pancake type in 65 K Sub-cooled LN_2.

The fault current was reduced to 1979 A at the first peak and 1041 A at the last peak at the test of solenoid type. In case of pancake type, the fault current was reduced to 2082 A at the first peak and 835 A at the last peak. The solenoid and the pancake type magnet limited the fault current to 46.6 % and 49 %, respectively at the first peak.

The generated resistance of each type magnet is shown in Fig. 6. The resistance pattern of pancake type magnet increased steeply compared with solenoid type magnet after the fault current flowed for 3 cycles, 0.05 second. Resistances of two types measured during the first 3 cycles of the fault current were independent of the magnet structure. The pancake type magnet was wound as if the tapes were stacked, so the generated heat would be accumulated in the magnet. The pancake type has higher resistance in the same fault condition. The resistance of the solenoid type magnet has gentle slope after 0.05 s from the fault. The cooling of the solenoid winding is more efficient than the pancake winding, because winding surface of the solenoid winding is more exposed to the coolant. It means that the solenoid type is thermally stable. The recovery of the solenoid type magnet was faster than that of the pancake type magnet. The solenoid type magnet also would be expected to apply to the high voltage application. Though the resistance is zero below critical current, the non-inductively wound magnet has residual inductance which cause phase different voltage drop from current. The impedance before the fault seemed like a noise.

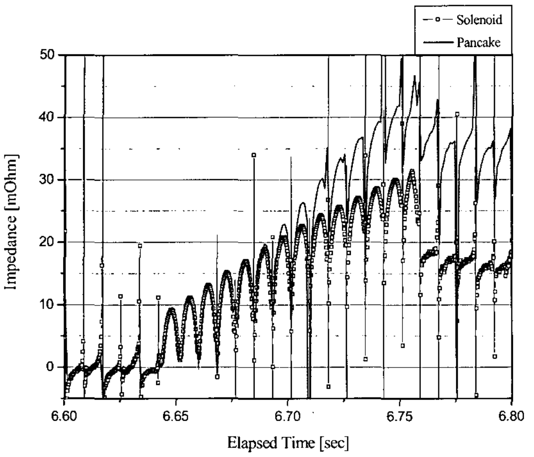


Fig. 6. Resistance of the solenoid type and the pancake type magnet at 29.1 V_{rms} test in 65 K Sub-cooled LN_2.

5. CONCLUSIONS

The short-circuit test was performed to analyze current limiting characteristic in sub-cooled nitrogen cooling system. The critical current and thermal stability were enhanced in sub-cooled nitrogen of 65 K. Though generated resistance was lower in 65 K than 77 K, the fault current was limited to 46.6 % and 49 % with the solenoid type and the pancake type magnets. The pancake type magnet generated higher resistance than the solenoid type, because the structure of the pancake type was able to accumulate the heat more than solenoid type and this would be able to be solved by enhancing cooling channel. Because the solenoid type magnet has lager exposed surface to the coolant, it has good characteristic of thermal stability related with the recovery time which is one of the important factors of FCL application. The non-inductively wound HTS magnet by using Bi-2223 wire showed good characteristic for SFCL application. This research verified the feasibility of magnets using HTS wires as the SFCL. We are planning to design, to manufacture the SFCL using the coated conductor, and to perform the short-circuit test from now on.

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